Invariant mass dependence of Λ polarization in $pp \to p\Lambda K^+\pi^+\pi^-\pi^+\pi^-$

Liang Zuo-tang and Li Tie-shi

Department of physics, Shandong University, Jinan Shandong 250100, China

Abstract

We show that there is a correlation between the invariant mass of the produced ΛK^+, $\Lambda K^+\pi^+\pi^-$ or $\Lambda K^+\pi^+\pi^-\pi^+\pi^-$ system in the exclusive reaction $pp \to p\Lambda K^+\pi^+\pi^-\pi^+\pi^-$ and the longitudinal or transverse momentum of Λ. Together with the longitudinal and transverse momentum dependence of Λ polarization observed in inclusive reactions, such a correlation implies a dependence of Λ polarization on these invariant masses. The qualitative features of this dependence are consistent with the recent observation by E766 collaboration at BNL. A quantitative estimation has been made using an event generator for pp collisions. A detailed comparison with the data is made.

Since the discovery[1] of hyperon polarization (P_H) in inclusive production processes at high energies, there has been constant interest in studying the origin of this effect, both experimentally[2] and theoretically [3-11]. It is now an established experimental fact that, in high energy hadron-hadron or hadron-nucleus collisions, the produced hyperons are polarized transversely to the production plane, although neither the projectiles nor the targets are polarized before the collisions. A large number of experiments on the inclusive production processes show that the polarization is significantly different from zero in the fragmentation regions for moderately large transverse momenta. The magnitude of the polarization increase with increasing x_F and $p_\perp$, where $x_F \equiv 2p_\parallel/\sqrt{s}$ is the Feynman-x, s is the total center of mass energy squared, $p_\parallel$ and $p_\perp$ are respectively the longitudinal and transverse component of the momentum of the produced hyperon.

Recently, further progresses have been achieved in experimental studies. An interesting program has been established by E766 Collaboration at Brookheaven National Laboratory (BNL) to study Λ polarization P_Λ in different specific reaction channels. The first experiment has already been carried out[12] on P_Λ in $pp \to p\Lambda K^+\pi^+\pi^-\pi^+\pi^-$. They found in particular the following interesting phenomenon: P_Λ in this channel depends not only on x_F and $p_\perp$ of the produced Λ (as observed earlier in inclusive experiments), but also on the invariant masses $M_{\Lambda K}$, $M_{\Lambda K\pi\pi}$, and $M_{\Lambda K\pi\pi\pi\pi}$, of the particle systems ΛK^+, $\Lambda K^+\pi^+\pi^-$ and $\Lambda K^+\pi^+\pi^-\pi^+\pi^-$ respectively. The magnitude of P_Λ increases with the increasing of these invariant masses $M_{\Lambda K}$, $M_{\Lambda K\pi\pi}$, and $M_{\Lambda K\pi\pi\pi\pi}$.

We recall that, compared with those on inclusive processes, the experiments on exclusive processes have the advantage to study the dependence on kinematic variables other than x_F or $p_\perp$. It offers the opportunity to investigate different correlations which usually provide us with information that can not be obtained in inclusive experiments. Such information gives often deeper insight into the physics behind the data. Hence, it is conceivable that the above mentioned new experimental finding provide further important tests of the different models and give us some new clue in the searching of the origin of Λ polarization in high energy hadron-hadron collisions. However, kinematic analysis readily shows that, due to

energy-momentum conservation, there has to be a correlation between the above-mentioned invariant mass $M_{\Lambda K}$, $M_{\Lambda K\pi\pi}$, or $M_{\Lambda K\pi\pi\pi\pi}$ and x_F or $p_\perp$ of Λ. On the average, both x_F and $p_\perp$ increase with the increasing of these invariant masses $M_{\Lambda K}$, $M_{\Lambda K\pi\pi}$, or $M_{\Lambda K\pi\pi\pi\pi}$. Together with the x_F and $p_\perp$ dependences of P_Λ observed earlier in the inclusive experiments, such correlations lead already to some increase of $|P_\Lambda|$ with the increasing of $M_{\Lambda K}$, $M_{\Lambda K\pi\pi}$, or $M_{\Lambda K\pi\pi\pi\pi}$. Hence, we are led naturally to the following questions: How large are these correlations? Can they already account for the observed invariant mass dependence of P_Λ? Do the observed increase of P_Λ with increasing $M_{\Lambda K}$, $M_{\Lambda K\pi\pi}$, or $M_{\Lambda K\pi\pi\pi\pi}$ give us some further tests of the different models or they are just different manifestations of the x_F and $p_\perp$ dependences observed earlier in inclusive experiments? These are questions which we would like to investigate in this note.

We recall that the invariant mass of ΛK^+-system is defined as the total energy in their center of mass (c.m.) system, i.e.,

$$M_{\Lambda K} = \sqrt{m_\Lambda^2 + p^{*2}} + \sqrt{m_K^2 + p^{*2}}, \tag{1}$$

where m_K and m_Λ are their masses, p^* is their momentum in the c.m. frame of this particle system. It is obvious that, $M_{\Lambda K}$ increases with increasing p^*. Large value of p^* implies that the difference between the momentum of Λ and that of K^+ is large, also in the c.m. frame of the colliding pp-system. Hence, we expect large difference between x_F (or $p_\perp$) of Λ and that of K^+ for large $M_{\Lambda K}$. On the other hand, if x_F is very large (say, larger than 0.5), the longitudinal momentum of Λ is very large. In this case, Λ carries already a very large part of the momentum of the whole system. According to energy-momentum conservation, the momentum of K^+ cannot be the same as that for Λ since the sum of them cannot exceed $\sqrt{s}/2$. The longitudinal momentum for K^+ has to be much smaller. This implies a large difference between them thus a large $M_{\Lambda K}$. Hence, we expect that $M_{\Lambda K}$ increases with increasing x_F for large x_F. Similarly, if $p_\perp$ of Λ is large, there should be a large probability that $p_\perp$ of K^+ is large and in the opposite direction to guarantee the transverse momentum conservation. This leads to a large difference in transverse momenta for Λ and K^+ thus also

a large $M_{\Lambda K}$. Hence, we expect $M_{\Lambda K}$ increases also with increasing $p_\perp$. We are naturally led to the following questions: How fast does $M_{\Lambda K}$ increase with increasing x_F or $p_\perp$? Are there similar correlations between $M_{\Lambda K\pi\pi}$ (or $M_{\Lambda K\pi\pi\pi\pi}$) and x_F or $p_\perp$ of Λ? Apparently, the answers to these questions are determined by the momentum distributions of the particles produced in the collision processes and these distributions can be obtained in unpolarized reactions.

In order to study these questions quantitatively, we used a Monte-Carlo event generator PYTHIA[13]. We recall that PYTHIA is an event generator for unpolarized high energy hadronic reactions based on Lund fragmentation model[14]. It describes most (if not all) of the different features of the data for particle production in unpolarized reactions. We therefore expect that we should be able to obtain a reasonable description of the correlations between x_F or $p_\perp$ and the invariant masses mentioned above. We generated 100,000 $pp \to p\Lambda K^+\pi^+\pi^-\pi^+\pi^-$ events using PYTHIA. From these events, we calculated the average values of x_F and those of $p_\perp$ for different $M_{\Lambda K}$, $M_{\Lambda K\pi\pi}$ or $M_{\Lambda K\pi\pi\pi\pi}$ bins. The obtained results are shown in Figs.1 and 2. From Figs.1(a) and 2(a), we see clearly that both $\langle x_F\rangle$ and $\langle p_\perp\rangle$ increase with increasing $M_{\Lambda K}$. This is consistent with our qualitative expectations. From Figs.1(b),1(c),2(b) and 2(c), we see also similar correlations between $M_{\Lambda K\pi\pi}$ or $M_{\Lambda K\pi\pi\pi\pi}$ and x_F or $p_\perp$. The average values $\langle x_F\rangle$ and $\langle p_\perp\rangle$ increase also with increasing $M_{\Lambda K\pi\pi}$ or $M_{\Lambda K\pi\pi\pi\pi}$. But, we also see that the magnitudes of these correlations are smaller than that between x_F or $p_\perp$ and $M_{\Lambda K}$.

Since the magnitude of Λ polarization P_Λ increases with increasing x_F or increasing $p_\perp$, we expect that $|P_\Lambda|$ has to increase also with $M_{\Lambda K}$, $M_{\Lambda K\pi\pi}$, or $M_{\Lambda K\pi\pi\pi\pi}$ because of the above mentioned correlations. This qualitative feature is in agreement with the data[12]. To see whether this effect explains also quantitatively the observed dependences of P_Λ on $M_{\Lambda K\pi\pi}$, $M_{\Lambda K\pi\pi}$ or $M_{\Lambda K\pi\pi\pi\pi}$, we did the following calculations. We assume that P_Λ is determined completely by the x_F and $p_\perp$ of Λ and use the x_F and $p_\perp$ dependences of P_Λ obtained in experiments on inclusive reactions as input to calculate P_Λ as a function of $M_{\Lambda K}$, that of $M_{\Lambda K\pi\pi}$ and that of $M_{\Lambda K\pi\pi\pi\pi}$ respectively. The results for P_Λ as a function of x_F and $p_\perp$

obtained earlier in inclusive experiments can be parametrized as[15]

$$P_\Lambda(x_F, p_\perp) = 1.5(c_1 x_F + c_2 x_F^3)(1 - e^{c_3 p_\perp^2}) \tag{2}$$

where $c_1 = -0.268 \pm 0.003$, $c_2 = -0.338 \pm 0.015$, and $c_3 = -4.5 \pm 0.6$, are constants determined by the data. Using this parameterization for $P_\Lambda(x_F, p_\perp)$, we obtain P_Λ as functions of $M_{\Lambda K}$, $M_{\Lambda K\pi\pi}$ and $M_{\Lambda K\pi\pi\pi\pi}$ shown in Fig.3.

From Fig.3, we see that, $|P_\Lambda|$ increases indeed with increasing $M_{\Lambda K}$, $M_{\Lambda K\pi\pi}$ or $M_{\Lambda K\pi\pi\pi\pi}$. This qualitative feature agrees with the data[12]. We see also that, the $M_{\Lambda K}$ dependence of P_Λ agrees with the data even quantitatively.[16] This shows that the above mentioned kinematic effect together with the early observed x_F and $p_\perp$ dependences of P_Λ can already explain this $M_{\Lambda K}$ dependence. The qualitative features of P_Λ as a function of $M_{\Lambda K\pi\pi}$ and that of $M_{\Lambda K\pi\pi\pi\pi}$ agree also with the data. But, quantitatively, the increase of $|P_\Lambda|$ is too slow and is not enough to account for the observed $M_{\Lambda K\pi\pi}$ or $M_{\Lambda K\pi\pi\pi\pi}$ dependence. In particular, $|P_\Lambda|$ seems too large near the threshold of $M_{\Lambda K\pi\pi}$ or $M_{\Lambda K\pi\pi\pi\pi}$. This means that other dynamic effects have to be introduced to account for this effect. This also implies that these dependences should be other independent tests for the different theoretical models [4-11].

In summary, we made a kinematic analysis of the dependence of P_Λ in $pp \to p\Lambda K^+\pi^+\pi^-\pi^+\pi^-$ on the invariant masses of the produced ΛK^+, $\Lambda K^+\pi^+\pi^-$ and $\Lambda K^+\pi^+\pi^-\pi^+\pi^-$ systems. We showed that there is a correlation between these invariant masses and x_F or $p_\perp$ of Λ. This correlation gives already a reasonable explanation of the increase of $|P_\Lambda|$ with increasing $M_{\Lambda K}$ but not that with increasing $M_{\Lambda K\pi\pi}$ or $M_{\Lambda K\pi\pi\pi\pi}$.

We thank Xie Qu-bing, Wang Qun, Si Zong-guo for helpful discussions. This work is supported in part by the National Natural Science Foundation (NSFC) and the Education Ministry of China.

REFERENCES

1. A. Lesnik *et al.,* Phys. Rev. Lett. **35**, 770 (1975); G. Bunce *et al.*, Phys. Rev. Lett. **36**, 1113, (1976).

2. A review of data can be found, e.g., in K. Heller, Proceedings of the 12th International Symposium on High Energy Spin Physics, 1996, Amsterdam, edited by C.W. de Jager *et al.*,, World Scientific (1997), p.23.

3. G. Kane, J. Pumplin, W. Repko, Phys. Rev. Lett. **41**, 1689 (1978).

4. B. Andersson, G. Gustafson and G. Ingelman, Phys. Lett. **85B**, 417 (1979).

5. T.A. DeGrand and H.I. Miettinen, Phys. Rev. **D24**, 2419 (1981).

6. J. Szwed, Phys. Lett. **105B**, 403 (1981).

7. L. G. Pondrom, Phys. Rep. **122**, 57 (1985).

8. R. Barni, G. Preparata and P.G. Ratcliffe, Phys. Lett. **B296**, 251 (1992).

9. J. Soffer and N. Törnqvist, Phys. Rev. Lett. **68**, 907 (1992).

10. W.G.D. Dharmaratna, G.R. Goldstein, Phys. Rev. D**53**,1073 (1996); G.R. Goldstein, TUFTS-TH-99-G02, hep-ph/9907573 (1999).

11. Liang Zuo-tang, and C. Boros, Phys. Rev. Lett. **79**, 3608 (1997).

12. BNL E766 Collaboration, J. Félix *et al*, Phys. Rev. Lett. **76**, 22 (1996).

13. T. Sjöstrand, Comp. Phys. Comm. **39**, 347 (1986).

14. B. Anderson, G. Gustafson, G. Ingelman, and T.Sjöstrand, Phys. Rep. **97**, 31 (1983).

15. B. Lundberg *et al.*, Phys. Rev. **D40**, 3557 (1989).

16. It should be mentioned in this connection that similar measurements have been carried out by R608 Collaboration at CERN for the diffractive process $pp \to p\Lambda K^+$ at $\sqrt{s} = 63$

GeV (see [17]) and similar increase of $|P_\Lambda|$ with $M_{\Lambda K}$ has also been reported. Clearly, the same kinematic effect as we discussed above for $pp \to p\Lambda K^+\pi^+\pi^-\pi^+\pi^-$ exists also here, i.e., the $\langle x_F \rangle$ and $\langle p_\perp \rangle$ for Λ in this process increase also with increasing $M_{\Lambda K}$. Together with the x_F dependence of P_Λ observed in $pp \to \Lambda X$, this effect leads to an increase of $|P_\Lambda|$ with $M_{\Lambda K}$, which agree qualitatively with the data. It would be interesting also to extend our quantitative estimations to this process to see if the observed $M_{\Lambda K}$ dependence of P_Λ can also be attributed to such effect. This is unfortunately impossible at present, since the x_F values reached in the R608 experiment can be as large as 0.96 which is far beyond the x_F region where we have data for P_Λ in $pp \to \Lambda X$. It is unclear whether the parameterization of P_Λ as a function of x_F and $p_\perp$ given in Eq.(2) is still valid for such large x_F and this parameterization plays an essential role in our estimation. Hence, presently we can only conclude that, there is definitely contribution from the above-mentioned kinematic effect to the $M_{\Lambda K}$ dependence of P_Λ in that diffractive process, but we cannot say whether this contribution can already account for the increase observed in the experiment.

17. E608 Collaboration, T. Henkes *et al.*, Phys. Lett. B **283**, 155 (1992).

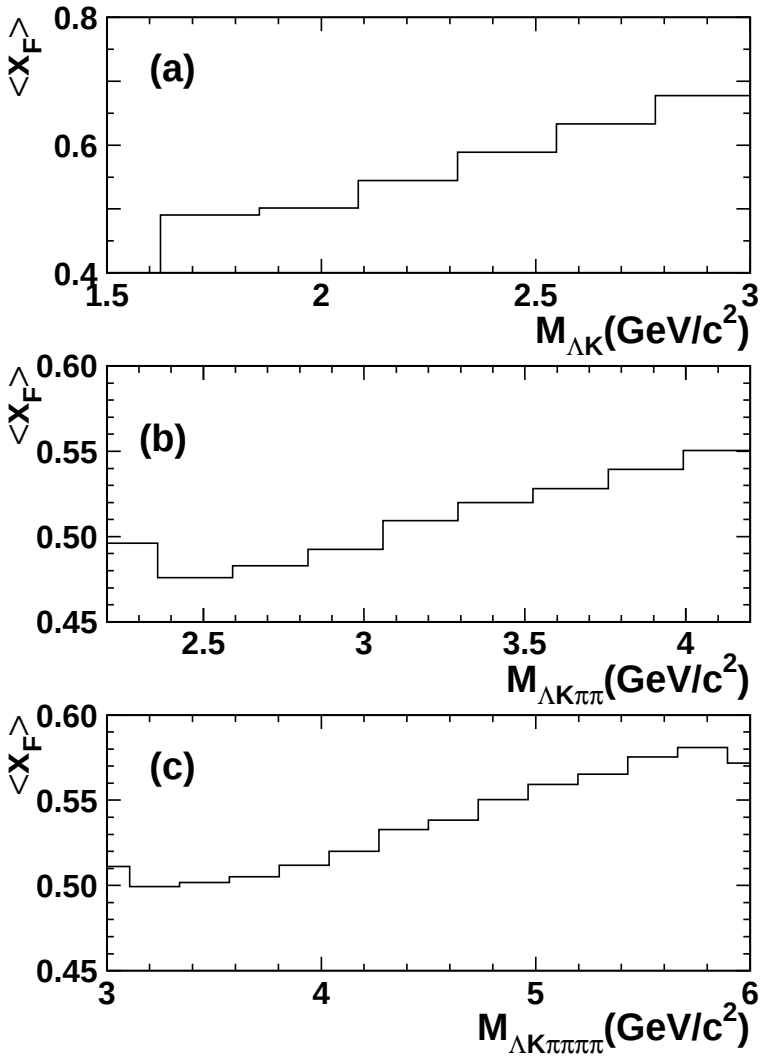

Fig. 1. Average values of x_F of Λ as a function of the invariant mass (a) $M_{\Lambda K}$, (b) $M_{\Lambda K\pi\pi}$, or (c) $M_{\Lambda K\pi\pi\pi\pi}$ in $pp \to p\Lambda K^+\pi^+\pi^-\pi^+\pi^-$ at 27.5GeV/c.

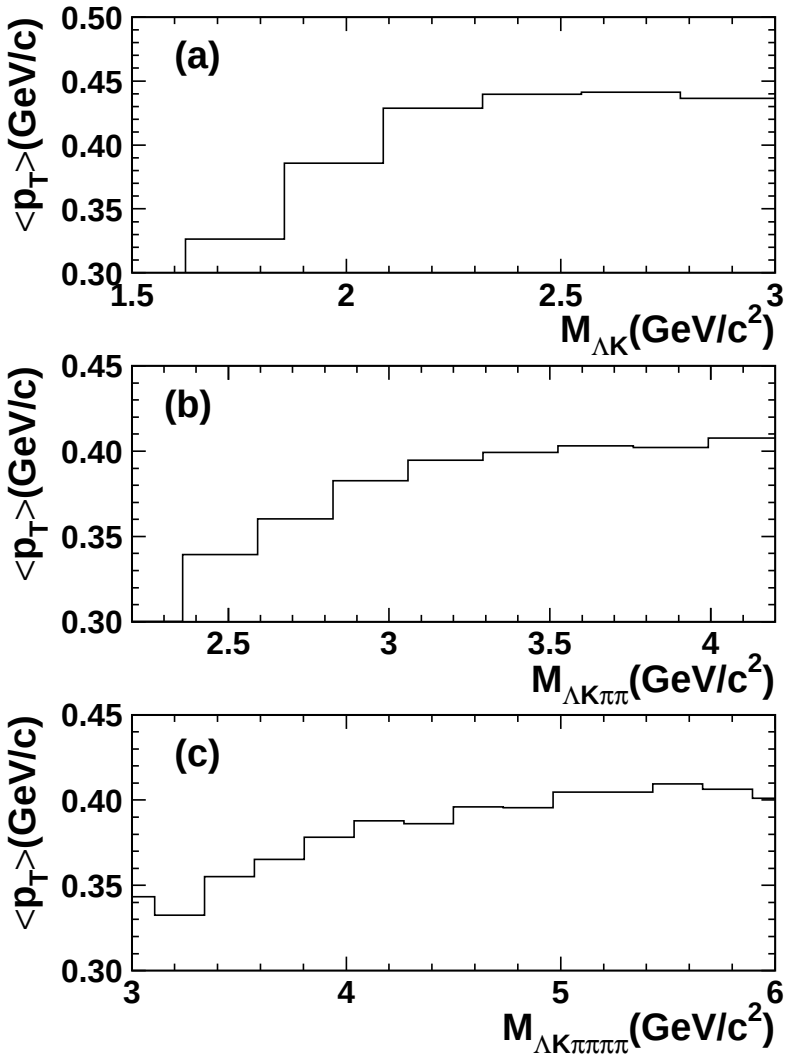

Fig. 2. Average values of $p_\perp$ of Λ as a function of the invariant mass (a) $M_{\Lambda K}$, (b) $M_{\Lambda K\pi\pi}$, or (c) $M_{\Lambda K\pi\pi\pi\pi}$ in $pp \to p\Lambda K^+\pi^+\pi^-\pi^+\pi^-$ at 27.5GeV/c.

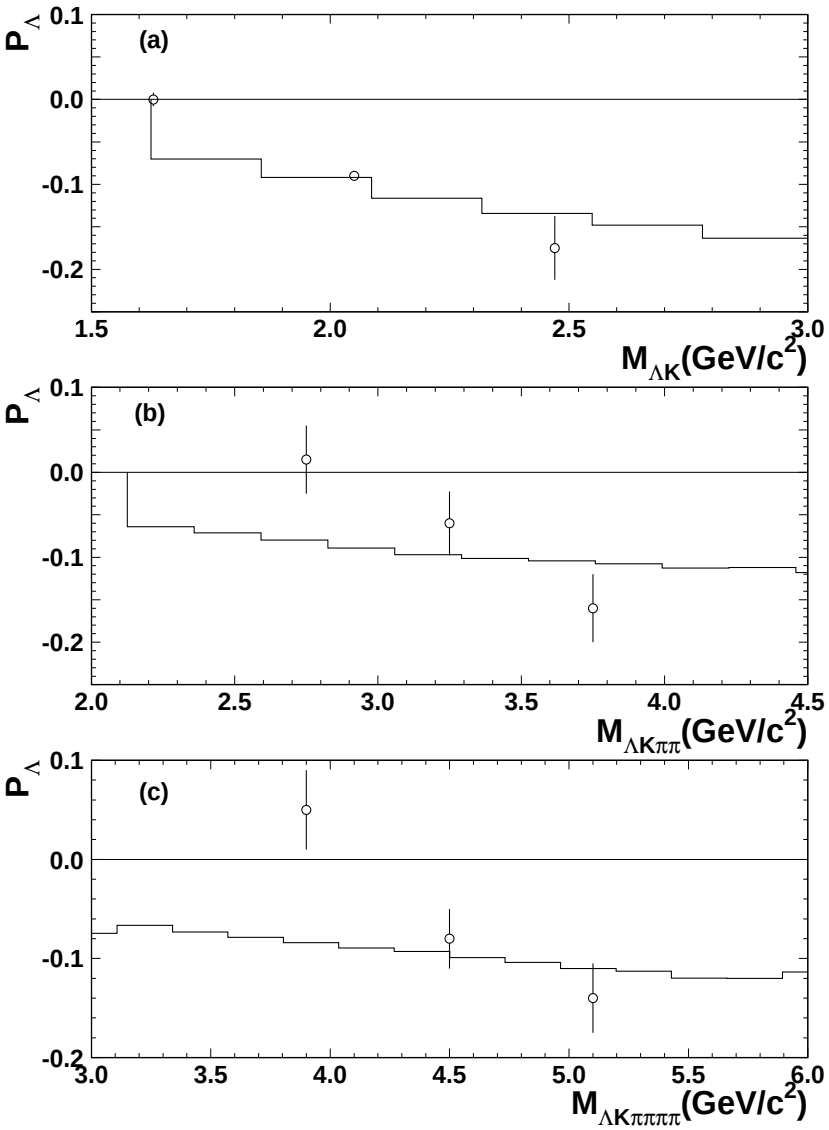

Fig. 3. Λ polarization as a function of the invariant mass (a) $M_{\Lambda K}$, (b) $M_{\Lambda K\pi\pi}$, or (c) $M_{\Lambda K\pi\pi\pi\pi}$ in $pp \to p\Lambda K^+\pi^+\pi^-\pi^+\pi^-$ at 27.5GeV/c. The data are taken from[12].